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(54) **RETINAL PROSTHESIS**

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See application file for complete search history.

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(57) **ABSTRACT**

An external device (**20**) includes a mount (**22**), which is placed in front of a subject's eye. A laser (**24**) is coupled to the mount (**22**) and emits radiation (**26**) that is outside of 380-750 nm. A partially-transparent mirror (**23**) is coupled to the mount (**22**). An intraocular device (**30**) is implanted entirely in the subject's eye, and includes a plurality of stimulating electrodes (**38**), and an energy receiver (**32**), which receives the radiation (**26**) from the laser (**24**) and generates a voltage drop. A plurality of photosensors (**34**) detect photons (**33**) and generate a signal. Driving circuitry (**36**) is coupled to the energy receiver (**32**) and to the photosensors (**34**), and receives the signals from the photosensors (**34**) and utilizes the voltage drop to drive the electrodes (**38**) to apply currents to the retina in response to the signals from the photosensors (**34**). Other embodiments are also described.

21 Claims, 4 Drawing Sheets

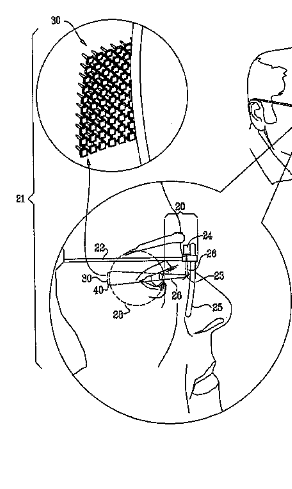

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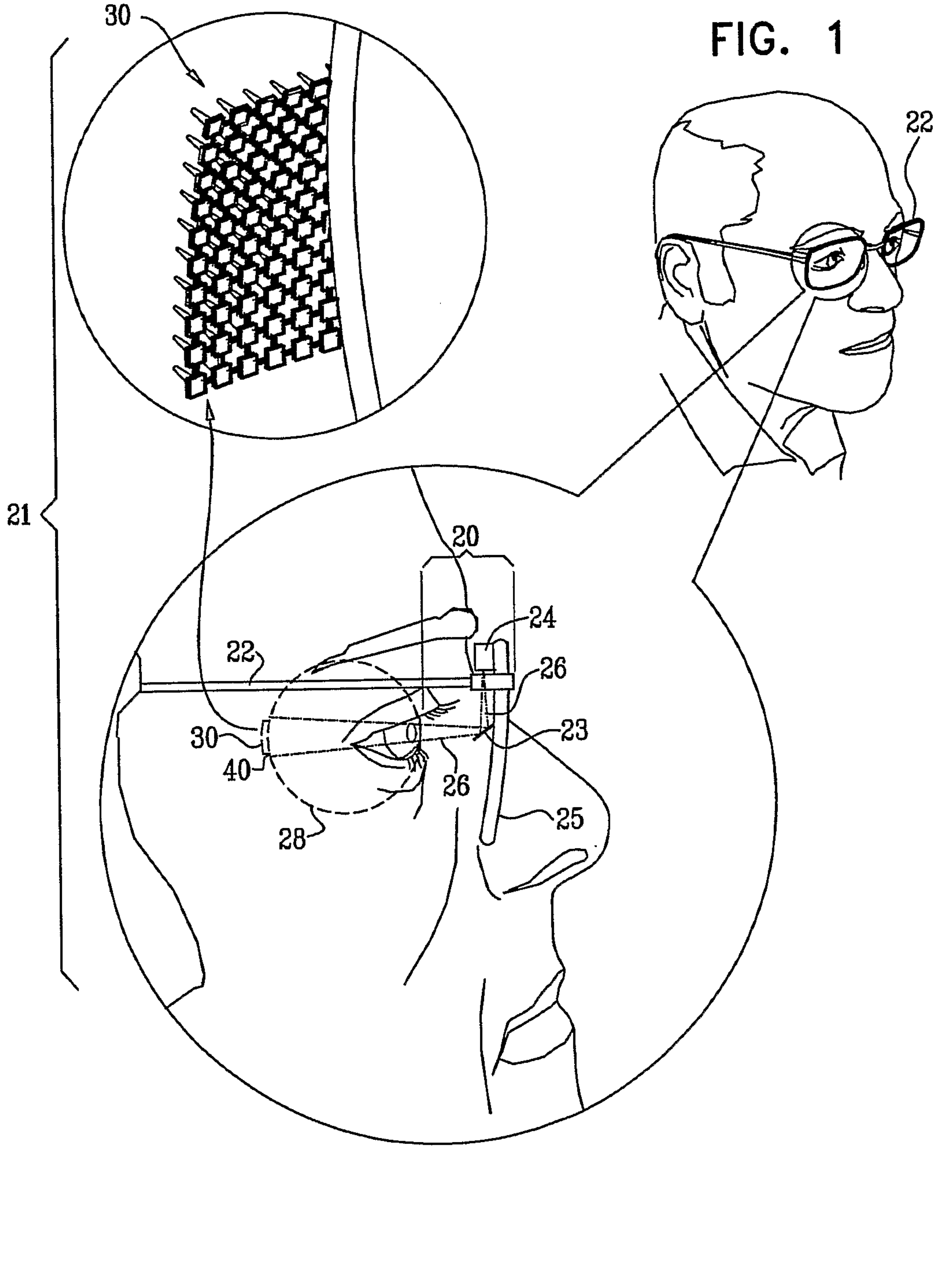
FIG. 1



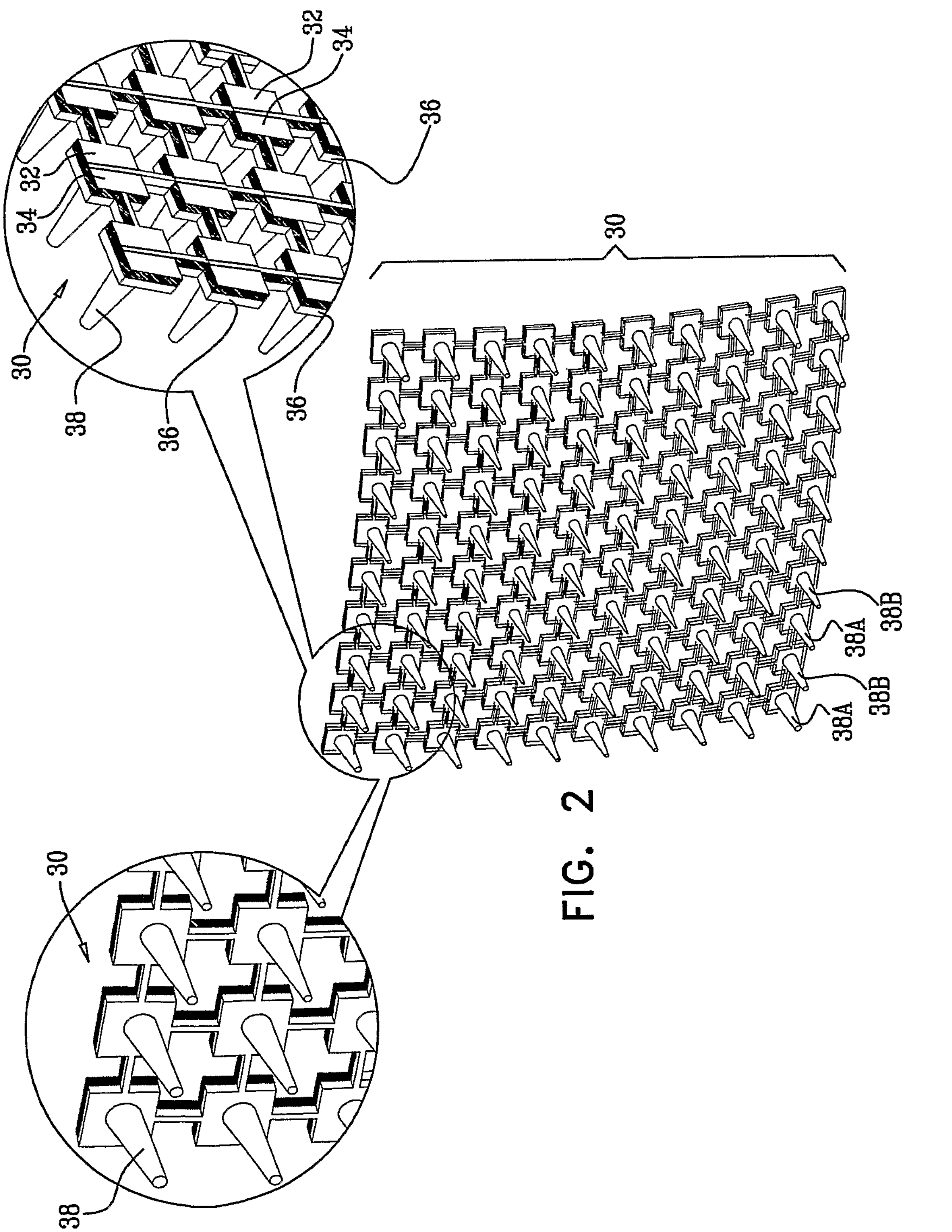
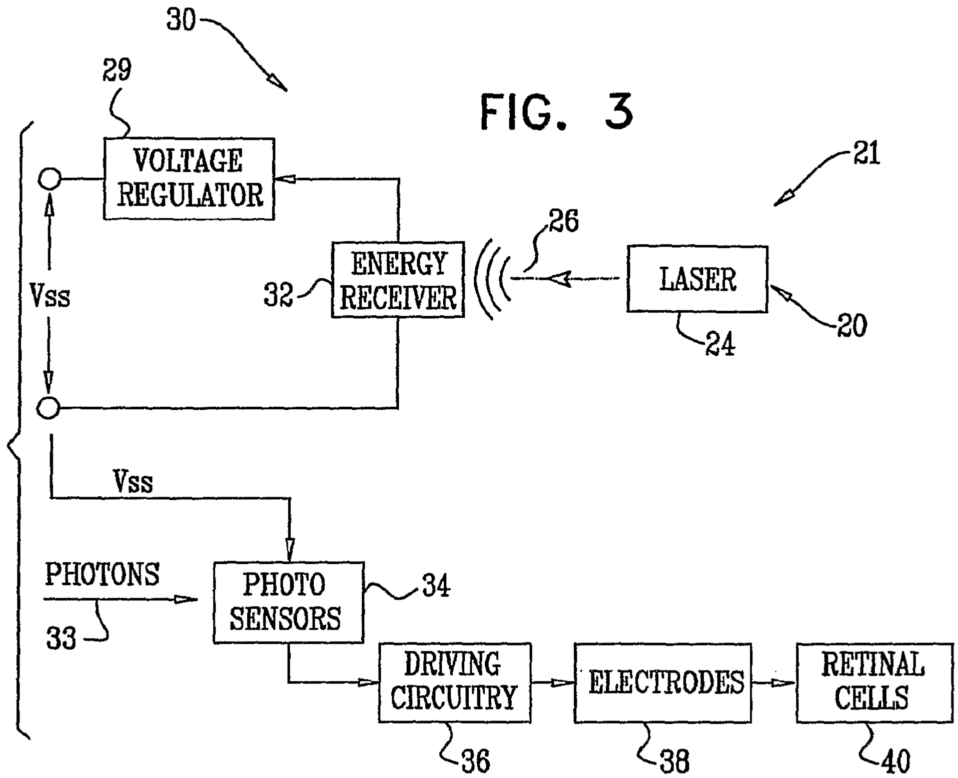


FIG. 2

FIG. 3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29
VOLTAGE REGULATOR
21
26
ENERGY RECEIVER
32
LASER
20
24
Vss
Vss
PHOTONS
33
PHOTO SENSORS
34
DRIVING CIRCUITRY
36
ELECTRODES
38
RETINAL CELLS
40

FIG. 4

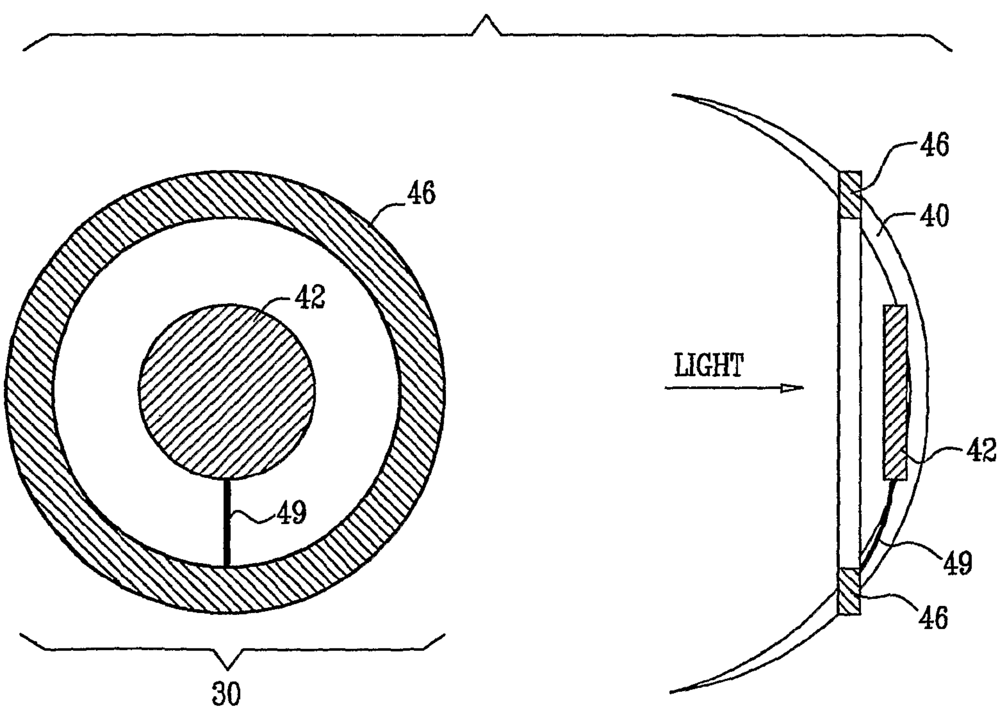

46
42
49
30
46
40
LIGHT
42
49
46

FIG. 5

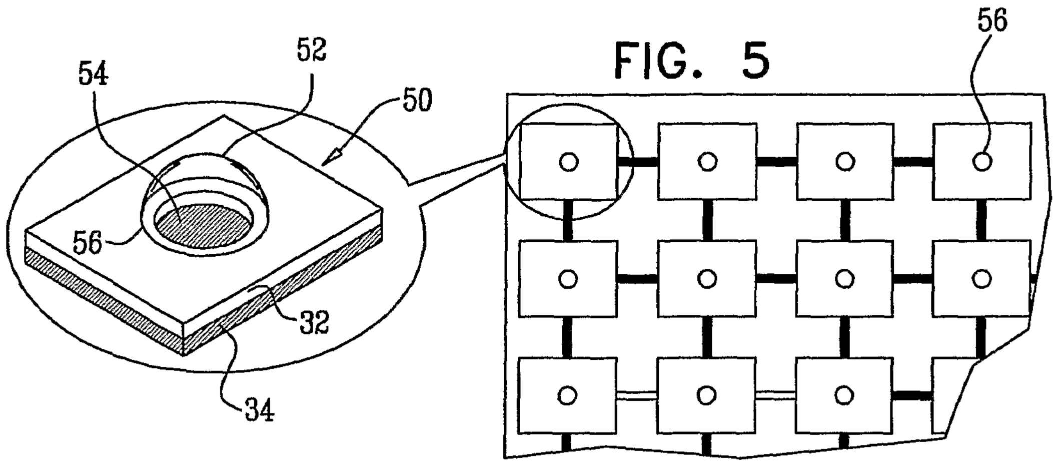


FIG. 6A

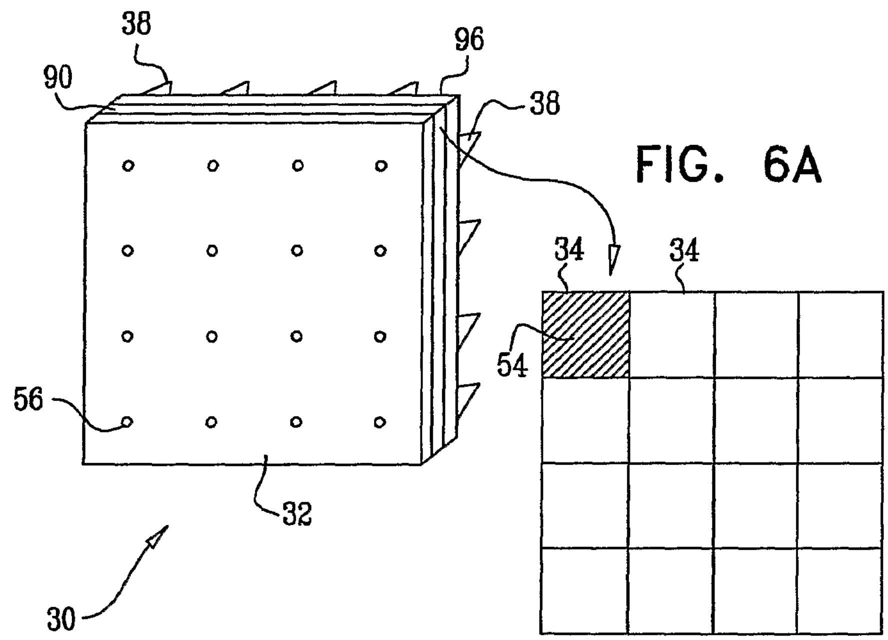
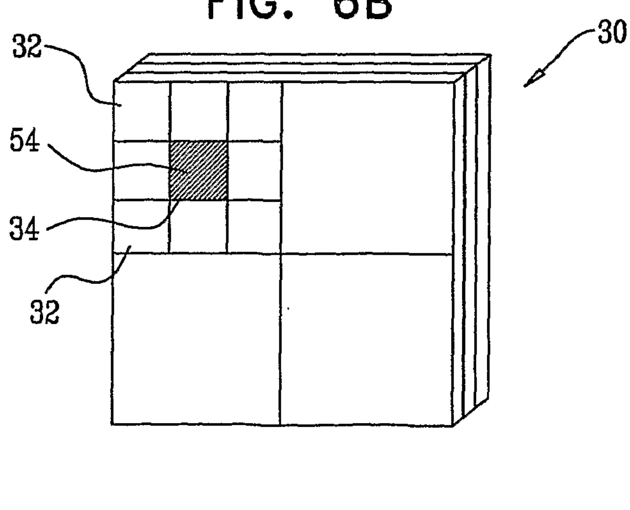


FIG. 6B



RETINAL PROSTHESIS

CROSS-REFERENCES TO RELATED APPLICATIONS

The present application is a U.S. national phase of PCT Application No. PCT/IL2010/000097 to Gross et al., filed Feb. 3, 2010, which published as WO/2010/089739 and claims the priority of U.S. patent application Ser. No. 12/368,150 to Gross et al., entitled, "Retinal Prosthesis," filed Feb. 9, 2009 and issued on Apr. 3, 2012 as U.S. Pat. No. 8,150,526 to Gross et al., which is incorporated herein by reference.

FIELD OF EMBODIMENTS OF THE INVENTION

Embodiments of the invention relate generally to implantable medical devices, and specifically to a retinal prosthesis.

BACKGROUND

Retinal malfunction, due to degenerative retinal diseases, is a leading cause of blindness and visual impairment. Implantation of a retinal prosthesis is a technology for restoring some useful vision in individuals suffering from retinal-related blindness.

The retina is a multi-layered light-sensitive structure that lines the posterior, inner part of the eye. The retina contains photoreceptor cells, for example rods and cones, which capture light and convert light signals into neural signals transmitted through the optic nerve to the brain. Rods are responsible for light sensitive, low resolution black and white vision, whereas cones are responsible for high resolution color vision. Most cones lie in the fovea, which defines the center of the retina.

U.S. Pat. No. 6,976,998 to Rizzo et al. describes an externally powered ocular device that is described as a safe and effective retinal prosthesis. The device is described as performing all functions needed of a retinal prosthesis with electronic components that are placed outside the wall of an eye, are powered wirelessly by an external power source, and which provide a patient with a view determined by natural motion of the eye and triggered by natural incident light converging at the retina. An externally powered, light-activated, sub-retinal prosthesis is described in which natural light entering the eye conveys visual details to the sub-retinal prosthesis, while wireless radiofrequency transmission provides the power needed to stimulate the retina, which would be insufficient if it were obtained from the intensity of incoming light alone.

U.S. Pat. No. 4,628,933 to Michelson describes a visual prosthesis for blindness due to retinal malfunction which includes a compact device having a close-packed array of photosensitive devices on one surface thereof. A plurality of electrodes extends from the opposed surface of the device and are connected to the outputs of the photosensitive devices. The device is adapted to be inserted in the posterior chamber of the eye, generally disposed at the focal plane of the optical pathway and impinging on the retina. Anchoring means secure the device with the electrodes operatively connected to the neuron array at the surface of the retina to stimulate the neurons in a pattern corresponding to the illumination pattern of the photosensitive array. The device is powered by externally induced electromagnetic or radio frequency energy, and is encased in a biologically inert housing. An amplifier array may be interposed between the sensing elements and the electrodes to amplify, shape, and time-process the visual signals.

U.S. Pat. No. 6,298,270 to Nisch describes a retina implant that has a substrate with a surface for applying same to a retina. The substrate comprises electrodes for stimulating cells within the retina. The electrodes are provided on the surface and are exposed to visible light impinging on the retina such that stimuli are exerted on the cells by the electrodes. The implant, further, comprises a photovoltaic layer responsive to non-visible light. The stimuli are locally switched utilizing a voltage generated by the photovoltaic layer.

U.S. Pat. No. 6,507,758 to Greenberg et al. describes a device for directly modulating a beam of photons onto the retinas of patients who have extreme vision impairment or blindness. Its purpose is to supply enough imaging energy to retinal prosthetics implanted in the eye which operate essentially by having light (external to the eye) activating photoreceptors, or photo-electrical material. The device is described as providing sufficient light amplification and does it logarithmically. While it has sufficient output light power, the output light level still remains at a described safe level. Most embodiments include balanced biphasic stimulation with no net charge injection into the eye. Both optical and electronic magnification for the image, as for example, using an optical zoom lens, is incorporated. It is described as being otherwise infeasible to zoom in on items of particular interest or necessity. Without proper adjustment, improper threshold amplitudes would obtain, as well as uncomfortable maximum thresholds. Therefore, to adjust for these, a way is described as providing proper adjustment for the threshold amplitudes and maximum comfortable thresholds. Furthermore, to the extent that individual stimulation sites in the retina give different color perceptions, upon stimulation, then colors of the viewed scene is correlated with specific stimulation sites to provide a certain amount of color vision.

U.S. Pat. No. 6,324,429 to Shire et al. describes a chronically-implantable retinal prosthesis for the blind, which is described as restoring some useful vision to patients. The epiretinal devices are described as thin, strong, and flexible and constructed of or encapsulated in known biocompatible materials, which are described as having a long working life in the eye's saline environment. The function of the implants is to electrically stimulate the ganglion cell layer at the surface of the retina using controlled current sources. The implant has planar form and is described as flexible and exceptionally low mass, minimizing patient discomfort and fluid drag. These physical attributes are described as substantially reducing the potential of harm to the most delicate structure of the eye, the retina, and therefore enhance the long term safety and biocompatibility of the device. Since no micro-cables are required to be attached to the device, and its overall form and edges are rounded, the device is described as not stressing the retina during chronic implantation. A provision is also made for nutrients to reach the retinal cells underneath the device to assure their long-term health. The device is meant to process and retransmit images and data to the ganglion cells on the retina surface.

U.S. Pat. No. 5,935,155 to Humayun et al. describes a visual prosthesis comprising a camera for perceiving a visual image and generating a visual signal output, retinal tissue stimulation circuitry adapted to be operatively attached to the user's retina, and wireless communication circuitry for transmitting the visual signal output to the retinal tissue stimulation circuitry within the eye. To generate the visual signal output, the camera converts a visual image to electrical impulses which are sampled to select an image at a given point in time. The sampled image signal is then encoded to allow a pixelized display of it. This signal then is used to modulate a radio frequency carrier signal. A tuned coil pair having a primary and a secondary coil is used to transmit and receive the RF modulated visual signal, which is then demodulated within the eye. The retinal stimulation circuitry includes a decoder for decoding the visual signal output into a plurality of individual stimulation control signals, which are used by current generation circuitry to generate stimulation current signals to be used by an electrode array having a plurality of electrodes forming a matrix. The intraocular components are powered from energy extracted from the transmitted visual signal. The electrode array is attached to the retina via tacks, magnets, or adhesive.

U.S. Pat. No. 7,047,080 to Palanker et al. describes a self-sufficient retinal prosthesis powered by intra-ocular photovoltaic cells illuminated only by ambient light. Photovoltaic cells can be disposed at the periphery of the retina or in the anterior chamber of the eye. An adaptive retinal prosthesis is also provided, such that the number of pixels energized in the prosthesis is selected according to the variable available power from ambient light.

U.S. Patent Application Publication 2006/0282128 to Tai et al. describes intraocular retinal prosthesis systems, and methods for fabricating such prostheses. A prosthesis device includes a cable region that connects an electrode array region with a power and data management region. The electrode array region includes one or more arrays of exposed electrodes, and the power and data management region includes various power and control elements. The power and data management elements, in one aspect, include an RF coil or coils and circuit arrangements and/or chips configured to provide drive signals to the electrodes via a cable and receive power and signals from the RF coil or coils. Each region includes elements fabricated on or in a single polymer layer during the same fabrication process.

U.S. Patent Application Publication U.S. 2007/0191909 to Ameri et al. describes a wide-field retinal prosthesis providing an increased field of vision with a relatively small scleral incision. The retinal prosthesis is described as including a flexible substrate comprising a central member and at least one wing, with an array of electrodes disposed therein that are configured to stimulate the central and peripheral nerves of the retina. The prosthesis can include a desired number of apertures for suitable flexibility.

U.S. Pat. No. 5,597,381 to Rizzo describes a method for epi-retinal implantation of an object into a subject. The method includes rendering the normally transparent cortical vitreous visible and separating at least a portion of a cortical vitreous of the subject away from an adherent retinal surface to form an epi-retinal space between the retina and the separated cortical vitreous material. An object to be implanted may be introduced into the epi-retinal space and the object engaged with a surface of the retina. In preferred embodiments, the object may then be adhered to the surface of the retina. A method for implantation of a neural contact structure for contact with neural tissue, for example, neural tissue of the retina within which are ganglion cells to be electrically stimulated is also described. The contact structure comprises a first portion for attachment to a first bodily location, such as the inner surface of the retina, and a second portion interconnected with the first portion via an interconnection and being held in contact with the neural tissue. The interconnection exhibits a weak restoring force which in conjunction with the geometry of the second portion provides a preselected desired pressure of contact against the neural tissue. As adapted for the retina, the interconnection exhibits a weak restoring force developed in response to curvature of the interconnection along the inner radius of the retina.

U.S. Pat. No. 6,368,349 to Wyatt et al. describes a neural prosthesis for implantation within an eye. The prosthesis includes a foldable substrate and at least one electronic component supported by the substrate. At least one microchannel is disposed within the substrate. Upon inflation, the foldable substrate is described as unfolding to provide for close contact of the electronic component with neural tissue, thus facilitating surgical implantation through a narrow incision, yet allowing the unfolded device to cover a sufficiently large portion of the patient's retina to provide useful vision.

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5,108,427
5,109,844
5,147,284
5,159,927
5,397,350
5,411,540
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6,658,299
6,755,530
7,003,354
7,006,873
7,027,874
7,031,776
7,037,943
7,103,416
7,139,612
7,162,308
7,251,528
7,321,796

PCT application WO 2007/09539

Zrenner E., 2002. "Will retinal implants restore vision?" Science 295(5557), pp. 1022-1025.

SUMMARY OF EMBODIMENTS OF THE INVENTION

In some applications of the present invention, apparatus is provided for restoring at least partial vision in a subject suffering from a retinal disease. The apparatus comprises an external device, comprising a mount that is placed in front of the subject's eye. The mount may be, for example, a pair of eyeglasses. The external device further comprises a power source, for example a laser that is coupled to the mount and is configured to emit radiated energy that is outside the visible range that is directed toward the subject's eye.

The apparatus additionally comprises an intraocular device, which is implanted entirely in the subject's eye. The intraocular device is configured to be implanted in the subject's eye in either an epi-retinal or a sub-retinal position. The intraocular device comprises a thin and typically flexible silicon array. The intraocular device comprises an energy receiver, which receives the radiated energy from the power source and generates a power signal to power other components of the intraocular device. The intraocular device further comprises an array, each unit of the array comprising a photosensor and a stimulating electrode. Each photosensor detects photons and generates a photosensor signal responsively to the photons. The photosensor signal is passed to driving circuitry, which uses energy from the energy receiver to drive the electrodes to apply currents to the retina. Stimulation of the retina elicits action potentials in the retinal ganglion cells, restoring some vision by activating the intact mechanisms of the eye.

There is therefore provided, in accordance with some applications of the invention, an apparatus including:

an external device including:

a mount, configured to be placed in front of an eye of a subject;

a laser coupled to the mount and configured to emit radiation that is outside of 380-750 nm; and

a partially-transparent mirror coupled to the mount; and

an intraocular device configured to be implanted entirely in the subject's eye, the intraocular device including:

an energy receiver, configured to receive the radiation from the laser and to generate a voltage drop in response thereto;

a plurality of stimulating electrodes;

a plurality of photosensors, each photosensor configured to detect photons and to generate a signal in response thereto; and

driving circuitry, coupled to the energy receiver and to the photosensors, and configured to receive the signals from the photosensors and to utilize the voltage drop to drive the electrodes to apply currents to a retina of the eye in response to the signals from the photosensors.

In some applications, the laser is configured to emit the light at 790-850 nm.

In some applications, the laser is configured to emit the light at 250-380 nm.

In some applications, the energy receiver is configured to receive light at 790-850 nm and to generate the voltage drop in response thereto.

In some applications, the energy receiver is configured to receive light at 250-380 nm and to generate the voltage drop in response thereto.

In some applications, the photosensors are generally insensitive to the energy from the laser.

In some applications, photosensors are generally sensitive to visible light.

In some applications, the energy receiver is configured to receive visible and non visible light, and to generate the voltage drop in response thereto.

In some applications, the intraocular device includes a filter configured to allow transmission to the photosensors of visible light only.

In some applications, the intraocular device includes a plurality of microlenses coupled to the energy receiver, facilitating refraction of visible light toward the photosensors.

In some applications, the intraocular device includes extending elements configured to provide anchoring of the intraocular device to the eye of the subject.

In some applications, the intraocular device includes extending elements to facilitate dissipation of heat away from at least the energy receiver.

In some applications, the electrodes include bipolar nanotube electrodes.

In some applications, the electrodes include monopolar nanotube electrodes.

In some applications, the electrodes include needle electrodes having exposed tips.

In some applications, the plurality of stimulating electrodes includes at least 100 electrodes.

In some applications, the intraocular device is configured to be implanted in an epi-retinal position.

In some applications, the intraocular device is configured to be implanted in a sub-retinal position.

In some applications, the apparatus includes a control element configured to receive an input from the subject, the external device is configured to modulate the energy emitted from the laser in response to the input, and the driving circuitry is configured to regulate a parameter of operation of the driving circuitry in response to the modulation of the energy emitted from the laser.

In some applications, the driving circuitry is configured to control an amount of stimulation per unit time applied by the electrodes, by the regulating of the parameter by the driving circuitry.

In some applications, the driving circuitry is configured to control an amplitude of the currents applied by the electrodes, by the regulating of the parameter by the driving circuitry.

In some applications, the driving circuitry is configured to control a sensitivity of the photosensors, by the regulating of the parameter by the driving circuitry.

In some applications, the external device includes a sensor coupled to the mount, configured to detect when an eyelid of the subject is closed, and the laser is configured to discontinue emission of the radiation when the eyelid is closed.

In some applications, the mount includes a filter configured to prevent transmission to the photosensors of ambient non-visible light.

In some applications, the filter includes a Schott filter.

In some applications, the driving circuitry is disposed in a single area of the intraocular device, and is configured to drive all of the electrodes.

In some applications, the apparatus includes a plurality of driving circuitries, each driving circuitry configured to drive a respective subset of electrodes.

In some applications, the plurality of driving circuitries includes 10-300 driving circuitries.

In some applications, the plurality of driving circuitries includes 300-3000 driving circuitries.

There is further provided in accordance with some applications of the invention apparatus, including:

an external device, including:

a mount, configured to be placed in front of an eye of a subject; and

a laser coupled to the mount and configured to emit radiation that is outside of 380-750 nm; and

an intraocular device configured to be implanted entirely in the subject's eye, the intraocular device including:

an energy receiver, configured to receive the radiation from the laser and to generate a voltage drop in response thereto;

a plurality of stimulating electrodes;

a plurality of photosensors, each photosensor configured to detect photons and to generate a signal in response thereto; and

driving circuitry, coupled to the energy receiver and to the photosensors, and configured to receive the signals from the photosensors and to utilize the voltage drop to drive the electrodes to apply currents to a retina of the eye in response to the signals from the photosensors,

and the external device is configured to modulate the radiation emitted from the laser, and the driving circuitry is configured to regulate a stimulation parameter of operation of the driving circuitry in response to the modulation of the radiation emitted from the laser.

In some applications, the driving circuitry is configured to drive the electrodes to apply the currents in pulses of current, and the stimulation parameter is selected from the group consisting of: a number of the pulses, a frequency of the pulses, a duration of each pulse, and a pulse repetition interval of the pulses.

There is additionally provided in accordance with some applications of the invention, a method for supplying power to a retinal implant, including:

emitting radiation from a laser, in a direction that is not toward the implant; and

receiving the radiation from the laser, by the implant.

In some applications, emitting the radiation comprises causing the radiation to be redirected toward the implant by a partially-transparent mirror.

There is yet further provided in accordance with some applications of the invention, a method for modulating stimulation parameters of an implant configured for implantation in a subject, the method including:

emitting laser radiation, from a laser to the implant;

receiving an input from the subject, and in response to receiving the input from the subject, modulating the radiation emitted from the laser; and

regulating a stimulation parameter of driving circuitry of the implant in response to the modulation of the radiation emitted from the laser.

In some applications, regulating the stimulation parameter includes:

driving currents into electrodes of the implant in pulses; and

in response to the modulation of the radiation, regulating at least one parameter selected from the group consisting of a number of the pulses, a frequency of the pulses, a duration of each pulse, and a pulse repetition interval of the pulses.

The present invention will be more fully understood from the following detailed description of embodiments thereof, taken together with the drawing, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of apparatus for restoring at least partial vision in a subject, in accordance with some applications of the present invention;

FIG. **2** is a schematic illustration of an intraocular device, in accordance with some applications of the present invention;

FIG. **3** is a block diagram of the transmission of energy in the apparatus for restoring vision, in accordance with some applications of the present invention;

FIG. **4** is a schematic illustration of the intraocular device, in accordance with some applications of the present invention;

FIG. **5** is a schematic illustration of an energy receiver-photosensor unit, in accordance with some applications of the present invention; and

FIGS. **6**A and **6**B are schematic illustration of layered structures of the intraocular device, in accordance with respective applications of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

FIG. **1** is a schematic illustration of apparatus **21** for_restoring at least partial vision in a subject suffering from retinal malfunction, in accordance with some applications of the present invention. Apparatus **21** comprises an external device **20** comprising a mount **22**, which is typically a pair of eyeglasses, and is placed in front of a subject's eye **28**. External device **20** further comprises a power source, for example a laser **24**, which is coupled to the mount and is configured to emit radiated energy **26**, which is outside the visible range, that is directed toward the subject's eye **28**. Laser **24** is shown coupled to the inner part of lens **25** by way of illustration and not limitation. Laser **24** may be coupled to other members of mount **22** for example, to the arm of the eyeglasses.

Apparatus **21** additionally comprises an intraocular device **30**, which is implanted entirely in eye **28**. Intraocular device **30** comprises a small e.g., 3-6 mm in diameter, thin e.g., less than 1 mm thick, and typically flexible silicon array.

Retinal implants are generally configured to be implanted in either a sub-retinal or an epi-retinal position. Epi-retinal arrays are typically implanted onto the retinal surface that separates the retinal neural layer from the vitreous body of the eye's posterior chamber. Epi-retinal implants are typically described as having no light sensitive areas and therefore receive electrical signals from a distant camera and processing unit outside of the subject's body. These described epi-retinal implants are coupled to the ganglion cells and their axons, and therefore directly simulate the ganglia (Zrenner 2002). In contrast, sub-retinal implants are typically implanted under the retina between the pigment epithelial layer and the outer layer of the retina which contains the photoreceptor cells. Sub-retinal implants typically stimulate the remaining neural cells of the retina (Zrenner 2002).

Intraocular device **30**, in accordance with some applications of the present invention, is configured to be implanted in either the epi-retinal or the sub-retinal space of eye. In both locations, intraocular device **30** receives visible light emanating from objects. The visible light strikes photosensors of the intraocular device, which generate a signal via intermediate circuitry causing electrodes on the intraocular device to stimulate retinal sensory neurons (for example the bipolar cells), resulting in the sensation of an image. Stimulation of the bipolar cells activates and utilizes the intact optics and processing mechanisms of the eye.

In some applications of the present invention, intraocular device **30** comprises needle electrodes with exposed tips configured to extend through the ganglion cells to directly contact and stimulate the bipolar cell layer, which in turn stimulates the ganglion cells, when intraocular device **30** is implanted in an epi-retinal position. The ganglion cells, whose axons form the optic nerve, further transmit the visual information to the brain. Apparatus **21** does not comprise a camera, and intraocular device does not receive image data, but rather utilizes the intact optics and processing mechanisms of eye.

In some applications of the present invention, intraocular device **30** is implanted in the subject's eye in a sub-retinal position. As described hereinabove, intraocular device **30** receives visible light emanating from objects. The visible light strikes the photosensors of the intraocular device, which generates a signal to drive electrodes **38** of the intraocular device. In applications in which intraocular device **30** is implanted in the sub-retinal space, the electrodes of intraocular device **30** are positioned in a suitable orientation allowing the electrodes to directly contact and stimulate the bipolar cells of the retina, which in turn stimulate the ganglion cells, resulting in image resolution. Similar to the implantation of intraocular device **30** in the epi-retinal position, implantation in the sub-retinal position also utilizes the intact optics and processing mechanisms of eye **28**.

FIG. **2** is a schematic illustration of intraocular device **30**, in accordance with some applications of the invention. Intraocular device **30** comprises an array, each unit of the array comprising an energy receiver **32** which receives radiated energy **26** from laser **24** of external device **20** (FIG. **1**). Energy receiver **32** generates a power signal to power other components of intraocular device **30**. Alternatively, a single energy receiver **32** (or a small number of receivers **32**) is configured to receive radiated energy **26** from laser **24**, to power the components of the entire intraocular device **30**. Each unit of the intraocular device **30** further comprises a photosensor **34**, a stimulating electrode **38**, and driving circuitry **36**. A signal generated by photosensor **34** is passed to driving circuitry **36**, which utilizes energy from the energy receiver **32** to drive electrode **38** to stimulate the retina. Alternatively, some or all of electrodes **38** are driven by driving circuitry **36** in a single area of intraocular device **30** (rather than by discrete driving circuitry physically located next to each electrode). Accordingly, for some applications, intraocular device **30** may comprise a plurality of driving circuitries, e.g., 10-3000 driving circuitries, each driving circuitry being configured to drive a respective subset of electrodes.

It is noted that FIG. **2** shows intraocular device **30** configured for epi-retinal implantation. In another application, electrodes **38** extend from intraocular device **30** in the direction of the pupil, and intraocular device **30** is implanted sub-retinally (configuration not shown).

Reference is now made to FIGS. **1** and **2**. External device **20** further comprises ophthalmoscope functionality, including a partially-transparent (e.g., half-silvered) mirror **23** coupled to a lens **25** of mount **22**. The partial transparency of mirror **23** allows energy from laser **24** to reach energy receiver **32** without the physical apparatus of laser **24** occluding vision. Additionally, light from the environment which forms images on the array of photosensors **34** is able to pass through partially-transparent mirror **23**. The use of ophthalmoscope functionality as described further allows the use of a large diameter laser beam (e.g., 5-20 mm, such as 5-10 mm), which provide high total radiated energy **26**, while minimizing the density of the beam at the retina. If such a laser beam originated from a laser mounted on lens **25** itself, it would interfere with vision by blocking incoming light from the environment.

FIG. **3** is a block diagram of apparatus **21**, in accordance with some applications of the present invention. External device **20** (FIG. **1**) comprises laser **24**, which emits radiated energy **26** to power components of intraocular device **30**. Radiated energy **26** transmitted to the intraocular device **30** is received by energy receiver **32**. Energy receiver **32** typically comprises a voltage regulator **29** configured to maintain a constant voltage level to power the components of intraocular device **30**. Intraocular device **30** further comprises photosensors **34** configured to detect photons **33** and generate a photosensor signal responsively to the photons **33**. The photosensor signal is transmitted to driving circuitry **36**, which drives the electrode **38** to apply currents to retinal cells **40**.

FIG. **4** is a schematic illustration of intraocular device **30**, in accordance with some applications of the present invention. Intraocular device **30** comprises a generally small array **42**, e.g., 3-6 mm in diameter, and 1 mm thick. The array is surrounded by an additional toroidal array **46** that is physically associated with the rod cells area of the retina **40**, providing some degree of scotopic vision and/or wider-field vision. Arrays **42** and **46**, which generally function in a similar manner, are coupled by a multi-wire element **49**.

FIG. **5** is a schematic illustration of an energy receiver-photosensor unit **50**, in accordance with some applications of the present invention. Each energy receiver **32** has a hole **56** passing therethrough, through which light passes to strike a corresponding photosensor **34** located under the hole **56**. The energy-receiving portion of each energy receiver **32** is typically 50-250 um across (e.g., 75-150 um across), and the diameter of each hole is typically 10-120 um, e.g., 20-60 um. The energy-receiving area of each energy receiver is typically about 5-10 times greater than the area of each hole.

Photosensor **34** typically comprises a filter **54** allowing transmission of visible light, and blocking transmission of light emitted by laser **24**. As appropriate, filter **54** may allow substantially only visible light, or visible light and some non-visible light (e.g., near infrared) to strike the photosensor. Energy receiver **32** is typically optimized to transduce light of the wavelength of laser **24** into electricity, although it may alternatively be sensitive to a wider range of wavelengths, such as to both visible and non-visible light.

For some applications, energy receiver-photosensor unit **50** comprises a microlense **52**, which facilitates refraction of light toward photosensor **34** that would otherwise strike energy receiver **32**. Accordingly, microlense **52** comprises prism functionality, allowing for differential refraction of visible light and non-visible (power transmitting) light, such that the non-visible light lands on the energy receiver to power intraocular device **30**, while the visible light is refracted toward photosensors **34** which generate a signal in response to visible light photons. This provides some "averaging" of the light striking each photosensor, by combining that light with light that would otherwise strike the implant near the photosensor, thus mitigating the sensation of spaced individual pixels of light that may be sensed by a user with a retinal prosthesis. Using this technique, a slightly blurred image is intentionally formed, in which the extent of stimulation applied by a given electrode to the retina represents not only the light striking the very-small area of the corresponding photosensor, but also light that strikes the surrounding area under the microlense. (It is to be understood that in some embodiments, such a microlense is not provided.)

Reference is made to FIG. **6**A, which is a schematic illustration of intraocular device **30**, in accordance with some applications of the invention. In some embodiments of the present invention intraocular device **30** is assembled as a triple-layered device, comprising an energy receiving **32** top layer, a photosensor middle layer **90** and a driving circuitry layer **96**, coupled to electrodes **38**. Energy receiving **32** layer is configured to receive radiated laser energy, in order to power intraocular device **30**. Additionally, energy receiving **32** layer is shaped to define a plurality of holes **56** passing therethrough, through which light passes to strike photosensor layer **90** located under the holes **56**. The middle layer of intraocular device **30** comprises individual photosensor units **34**. Each photosensor unit typically comprises a filter **54** allowing transmission of visible light, and blocking transmission of light emitted by the laser. Visible light striking photosensor units **34** generates a current which is processed in the bottom, driving circuitry layer **96**, of intraocular device **30**. Driving circuitry layer **96** is coupled to electrodes **38** that stimulate the retinal cells to generate an image and restore vision.

It is noted that FIG. **6**A shows intraocular device **30** configured for epi-retinal implantation. In another application, electrodes **38** extend from the energy receiving **32** layer, and intraocular device **30** is implanted sub-retinally (configuration not shown).

Reference is made to FIG. **6**B, which is a schematic illustration of intraocular device **30**, in accordance with another application of the invention. In this application, the top layer of intraocular device **30** comprises both energy receivers **32** and photosensors **34**. For example, the top layer of intraocular device **30** may comprise an array divided into sub-arrays. Each sub-array is further divided into (for example) nine units each. The central unit of each sub-array comprises a photosensor **34**, typically comprising a filter **54** which passes visible light. The surrounding units in each sub-array are energy receiving units **32**, receiving radiated laser energy to power intraocular device **30**. As appropriate, electrodes **38** may be coupled to the top layer, for sub-retinal implantation, or to the bottom layer, for epi-retinal implantation.

Typically, apparatus **21** activates and utilizes the intact optic mechanisms, natural movements, and focusing of eye **28**. Furthermore, intraocular device **30** is typically a small and flexible device e.g., 3-6 mm in diameter, and less than 1 mm thick, implanted in a either an epi-retinal or a sub-retinal position, and powered by an external power source e.g., a laser. Therefore, intraocular device **30** is wireless, does not comprise bulky components, and does not require power-consuming internal microcontrollers. Additionally, energy receiver **32**, receiving radiated energy **26**, for example laser energy, is typically fine-tuned to match a specific laser wavelength (for example an IR wavelength such as 790-850 nm, or a suitable UV wavelength). Therefore, a substantial portion of radiated energy **26** is utilized to power electrodes **38**, allowing for an increased number of electrodes **38** and thereby resulting in enhanced image resolution. For example, if a total of 35 mW of laser energy reaches intraocular device **30**, this provides an estimated 14 mW of usable electricity (assuming an approximate 40% efficiency rate).

For some applications electrodes **38** are bipolar or alternatively monopolar nanotube electrodes coated with carbon nanotubes.

The number of electrodes per array typically ranges between 100-10,000 electrodes. In some applications, a relatively smaller number of electrodes (e.g., 100-1,000) are in generally continuous use, while a higher number of electrodes (e.g., 1,000-10,000), which are not continuously activated, can enable the subject to temporarily increase resolution at the cost of heating of the eye for several seconds. Additionally or alternatively, intraocular device **30** comprises interleaved arrays of electrodes **38***a* and **38***b*, which are activated separately, thus stimulating adjacent retinal sites and generating the illusion of higher-resolution of an actual image.

In some applications of the present invention, intraocular device **30** comprises support elements extending away from the retina. Support elements are typically composed of biocompatible materials (for example, PtIr), possibly insulated with an additional biocompatible material. The support elements aid in anchoring implanted intraocular device **30** to the subject's eye **28**. Additionally or alternatively, the support elements contribute to enhanced dissipation of heat, preventing local overheating of eye **28**. The total volume of support elements is typically similar to the volume of intraocular device **30** (for example, 25 mm3), allowing for efficient heat dissipation.

In some applications of the present invention, external device **20** comprises a sensor coupled to mount **22**. Apparatus **21** is configured to detect blinking, and to not transmit power to intraocular device **30** when the subject's eyelid is closed. The sensor is configured to detect the rapid closing and opening of the eyelid of the subject, and to signal to laser **24** to cease emitting radiation **26** to the eye when the eyelid of the subject is closed. For some applications, the sensor comprises an electromyography (EMG) sensor or a camera with image processing functionality to determine when the eye is closed. For some applications, the sensor comprises a light sensor coupled to a light emitting diode (LED), which is located adjacent to laser **24**. The LED emits light which passes through partially-transparent mirror **23** and is directed towards the subject's eye **28**. The amount (or another parameter) of reflected LED light from the eye changes as a result of the subject's blinking. These changes in the amount of the reflected light are detected by the light sensor, which causes laser **24** to discontinue emitting radiation **26** to eye **28** when the eyelid of the subject is closed. Alternatively, for some applications, mount **22** comprises a light sensor located in proximity to laser **24**. The light sensor detects reflected laser light, and laser **24** discontinues emitting radiation **26** to the eye when the eyelid of the subject is closed.

In some embodiments of the present invention, apparatus **21** is configured to provide the subject with audio feedback advising the subject to aim eye **28** so that radiation from laser **24** reaches intraocular device **30**. Accordingly, for some applications, external device **20** comprises a light sensor coupled to laser **24**, configured to detect the amount of reflected laser light and to trigger an audio signal to the subject based on changes in the reflected light indicative of the laser light not being directed toward intraocular device **30**. For example, a different portion of the laser light is absorbed by intraocular device **30** when laser **24** is properly aimed, compared to when the laser beam is diverted and not directed at eye **28**. In this latter case, the audio feedback signal is triggered.

For some applications, in addition to supplying power to device **30**, radiation **26** emitted by laser **24** is used to regulate operation of intraocular device **30**. In some applications of the present invention, external device **20** comprises a control element (e.g., a dial, switch, or button) coupled to mount **22**, allowing the subject to interactively control the intensity of the signal applied to the retina and/or the sensitivity of photosensors **34** to received light, and/or another system parameter. For example, if the subject determines that the overall stimulation being applied by intraocular device **30** to the retina is too strong, then he can adjust a setting on the control element to reduce the stimulation strength. Similarly, if he determines that the sensitivity of photosensors **34** is too high (e.g., resulting in the entire array of electrodes activating the retina), then he can adjust another setting on the control element to reduce the sensitivity. In response to the subject's input, control element **27** modulates radiation **26** emitted by laser **24** to regulate operating parameters of intraocular device **30**. An example of a suitable modulation protocol includes a first train of six short pulses from laser **24**, indicating that stimulation intensity is going to be changed, followed by a train of between one and ten longer pulses indicating a subject-selected desired level of stimulation intensity. To change sensitivity, a first train of six long pulses is emitted from laser **24**, followed by a train of between one and ten longer pulses indicating a subject-selected desired level of sensitivity. A person of ordinary skill in the art will appreciate that other encoding protocols may be used, as well.

Alternatively, for some applications, regulation of the intensity of the signal applied to the retina and/or the sensitivity of photosensors **34** to received light, and/or another system parameter, is regulated by intraocular device **30**. The degree of retinal stimulation applied by each unit of intraocular device **30** is dictated by the light received by that unit. Intraocular device **30** is configured to sense the amount of ambient light which is received by photosensors **34**, and in response, to alter the signal which is applied to the retina. For example, based on the amount of ambient light which lands on a given photosensor, intraocular device **30** is configured to modulate the signal by adjusting photosensor output and/or driving circuitry parameters such as gain and/or DC offset, allowing for increased sensitivity of apparatus **21**. Modulation of the signal applied to the retina is typically controlled by varying pulse parameters, e.g., of number of pulses, pulse repetition intervals, pulse frequency, and pulse duration. That is, electrodes **38** drive currents into the retinal neurons using pulse parameters selected in response to the amount of light received by the photosensor. Such modulation of photosensor pulse signals to the driving circuitry facilitates regulation of intraocular device **30**, for example, in response to changing levels of ambient light.

Similarly, the threshold for transmission of a photosensor signal to the driving circuitry i.e., the sensitivity of photosensors **34**, is regulated by the amount of ambient light reaching the photosensors. For some applications, the amount of ambient light that lands on the array of photosensors **34** is used to govern the duration of a sensing period of each photosensor, i.e., the amount of time in which the photosensor receives photons before the driving circuitry drives electrodes **38** to drive currents into retinal tissue (e.g., 10 ms-100 ms). Thus, for example, the sensitivity of each photosensor may be increased over the course of several seconds, if the subject enters a dark room.

Typically, regulation of system parameters of intraocular device **30**, by laser and/or by device **30** itself, is achieved by varying selected pulse parameters, e.g., the number of pulses, pulse repetition intervals, pulse frequency, and/or pulse duration.

As described hereinabove, in addition to powering intraocular device **30**, in some applications, radiation **26** emitted by laser **24** is additionally used to regulate operating parameters of intraocular device **30**. Laser **24** is typically configured to emit energy **26** that is outside the visible range and is directed toward the subject's eye **28**. For example, the radiation may be infrared (IR) radiation. For such applications, lens **25** of eyeglasses **22** may comprise an optical filter, e.g., a Schott filter. The filter is configured to filter IR radiation, thereby reducing the amount of ambient IR radiation that reaches photosensors **34** and may interfere with the IR radiation emitted by laser **24**. Radiated energy **26** is generally not affected by the filter placed on lens **25**, as laser **24** is typically coupled to the inner part of lens **25** as shown in FIG. **1**.

In some applications of the present invention, activation of apparatus **21** is regulated by a threshold to prevent saturation (i.e., over-stimulation of the retina by intraocular device **30**).

It is to be noted that a plurality of intraocular devices **30** may be implanted in discrete locations in tissue of the retina, either arranged in an array, or, for example, pseudo-randomly. Typically, intraocular device **30** is wireless and does not comprise bulky components, facilitating implantation of several intraocular devices **30** in the retina of a subject.

For some applications, techniques described herein are practiced in combination with techniques described in one or more of the following references, which are incorporated herein by reference:

U.S. Pat. No. 4,628,933 to Michelson
U.S. Pat. No. 5,597,381 to Rizzo
U.S. Pat. No. 5,935,155 to Humayun et al.
U.S. Pat. No. 6,298,270 to Nisch
U.S. Pat. No. 6,324,429 to Shire et al.
U.S. Pat. No. 6,368,349 to Wyatt et al.
U.S. Pat. No. 6,507,758 to Greenberg et al.
U.S. Pat. No. 6,976,998 to Rizzo et al.
U.S. Pat. No. 7,047,080 to Palanker et al.
U.S. Patent Application Publication 2006/0282128 to Tai et al.
U.S. Patent Application Publication U.S. 2007/0191909 to Ameri et al.

It will be appreciated by persons skilled in the art that the present invention is not limited to what has been particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and subcombinations of the various features described hereinabove, as well as variations and modifications thereof that are not in the prior art, which would occur to persons skilled in the art upon reading the foregoing description.

The invention claimed is:

1. Apparatus, comprising:

an external device, comprising:

a mount, configured to be placed in front of an eye of a subject; and

a power source coupled to the mount and configured to emit radiation that is outside of 380-750 nm; and

an intraocular device configured to be implanted entirely in the subject's eye, the intraocular device comprising:

an energy receiver, configured to receive the radiation from the power source and to generate a voltage drop in response thereto;

a plurality of stimulating electrodes;

a plurality of photosensors, each photosensor configured to detect photons and to generate a signal in response thereto; and

driving circuitry, coupled to the energy receiver and to the photosensors, and configured to receive the signals from the photosensors and to utilize the voltage drop to drive the electrodes to apply currents to a retina of the eye in response to the signals from the photosensors,

wherein the external device is configured to modulate the radiation emitted from the power source using an encoding protocol such that pulses of the radiation are encoded by the encoding protocol, and

wherein the driving circuitry is configured to regulate a parameter of operation of the driving circuitry in response to the modulation of the radiation emitted from the power source, and

wherein the driving circuitry is configured to control a sensitivity of the photosensors, by the regulating of the parameter by the driving circuitry.

2. The apparatus according to claim **1**, further comprising a partially-transparent mirror coupled to the mount.

3. The apparatus according to claim **1**, wherein the power source comprises a laser.

4. The apparatus according to claim **1**,

wherein the power source is configured to emit the radiation at 790-850 nm, and wherein the energy receiver is configured to receive radiation at 790-850 nm and to generate the voltage drop in response thereto.

5. The apparatus according to claim **1**, wherein the photosensors are generally insensitive to the radiation from the power source.

6. The apparatus according to claim **1**, wherein the photosensors are generally sensitive to visible light.

7. The apparatus according to claim **1**, wherein the intraocular device comprises a filter configured to allow transmission to the photosensors of visible light only.

8. The apparatus according to claim **1**, wherein the intraocular device further comprises extending elements to facilitate dissipation of heat away from at least the energy receiver.

9. The apparatus according to claim **1**, wherein the electrodes comprise needle electrodes having exposed tips.

10. The apparatus according to claim **1**, wherein the plurality of stimulating electrodes comprises at least 100 electrodes.

11. The apparatus according to claim **1**, wherein the intraocular device is configured to be implanted in an epi-retinal position.

12. The apparatus according to claim **1**, further comprising a control element coupled to the mount and configured to receive an input from the subject, and wherein the external device is configured to modulate the radiation emitted from the power source in response to the input.

13. The apparatus according to claim **1**, wherein the driving circuitry is configured to control an amount of stimulation per unit time applied by the electrodes, in response to the modulation of the radiation emitted from the power source.

14. The apparatus according to claim **1**, wherein the driving circuitry is configured to control an amplitude of the currents applied by the electrodes, in response to the modulation of the radiation emitted from the power source.

15. The apparatus according claim **1**, wherein the mount further comprises a filter configured to prevent transmission to the photosensors of ambient non-visible light.

16. The apparatus according to claim **1**, wherein

the driving circuitry is configured to drive the electrodes to apply the currents in stimulation pulses of current, and

the driving circuitry is configured to regulate a number of the stimulation pulses in response to the modulation of the radiation emitted from the power source.

17. The apparatus according to claim **1**, wherein

the driving circuitry is configured to drive the electrodes to apply the currents in stimulation pulses of current, and

the driving circuitry is configured to regulate a frequency of the stimulation pulses, in response to the modulation of the radiation emitted from the power source.

18. The apparatus according to claim **1**, wherein

the driving circuitry is configured to drive the electrodes to apply the currents in stimulation pulses of current, and

the driving circuitry is configured to regulate a duration of each stimulation pulse, in response to the modulation of the radiation emitted from the power source.

19. The apparatus according to claim **1**, wherein

the driving circuitry is configured to drive the electrodes to apply the currents in stimulation pulses of current, and

the driving circuitry is configured to regulate a pulse repetition interval of the stimulation pulses, in response to the modulation of the radiation emitted from the power source.

20. A method for modulating a parameter of an implant configured for implantation in a subject, the method comprising:

providing apparatus, comprising:

an external device, comprising:

a mount, configured to be placed in front of an eye of a subject; and

a power source coupled to the mount and configured to emit radiation that is outside of 380-750 nm; and

an intraocular device configured to be implanted entirely in the subject's eye, the intraocular device comprising:

an energy receiver, configured to receive the radiation from the power source and to generate a voltage drop in response thereto;

a plurality of stimulating electrodes;

a plurality of photosensors, each photosensor configured to detect photons and to generate a signal in response thereto; and

driving circuitry, coupled to the energy receiver and to the photosensors, and configured to receive the signals from the photosensors and to utilize the voltage drop to drive the electrodes to apply currents to a retina of the eye in response to the signals from the photosensors,

wherein the external device is configured to modulate the radiation emitted from the power source using an encoding protocol such that pulses of the radiation are encoded by the encoding protocol, and wherein the driving circuitry is configured to regulate a parameter of operation of the driving circuitry in response to the modulation of the radiation emitted from the power source, and wherein the driving circuitry is configured to control a sensitivity of the photosensors, by the regulating of the parameter by the driving circuitry,

emitting the radiation, from the power source to the intraocular device;

receiving an input from the subject, and in response to receiving the input from the subject, modulating the radiation emitted from the power source by using the encoding protocol such that the pulses of the radiation are encoded by the encoding protocol;

regulating the parameter of the driving circuitry of the intraocular device in response to the modulation of the radiation emitted from the power source; and

controlling the sensitivity of the photosensors, by the regulating of the parameter by the driving circuitry.

21. The method according to claim **20**, wherein the method further comprises:

using the driving circuitry, driving currents into the electrodes of the intraocular device in stimulation pulses; and

in response to the modulation of the radiation, regulating at least one stimulation parameter selected from the group consisting of: a number of the stimulation pulses, a frequency of the stimulation pulses, a duration of each stimulation pulse, and a pulse repetition interval of the stimulation pulses.

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